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FEASIBILITY STUDY FOR RAILROAD EMBANKMENT EVALUATION WITH RADAR--ETC(U)
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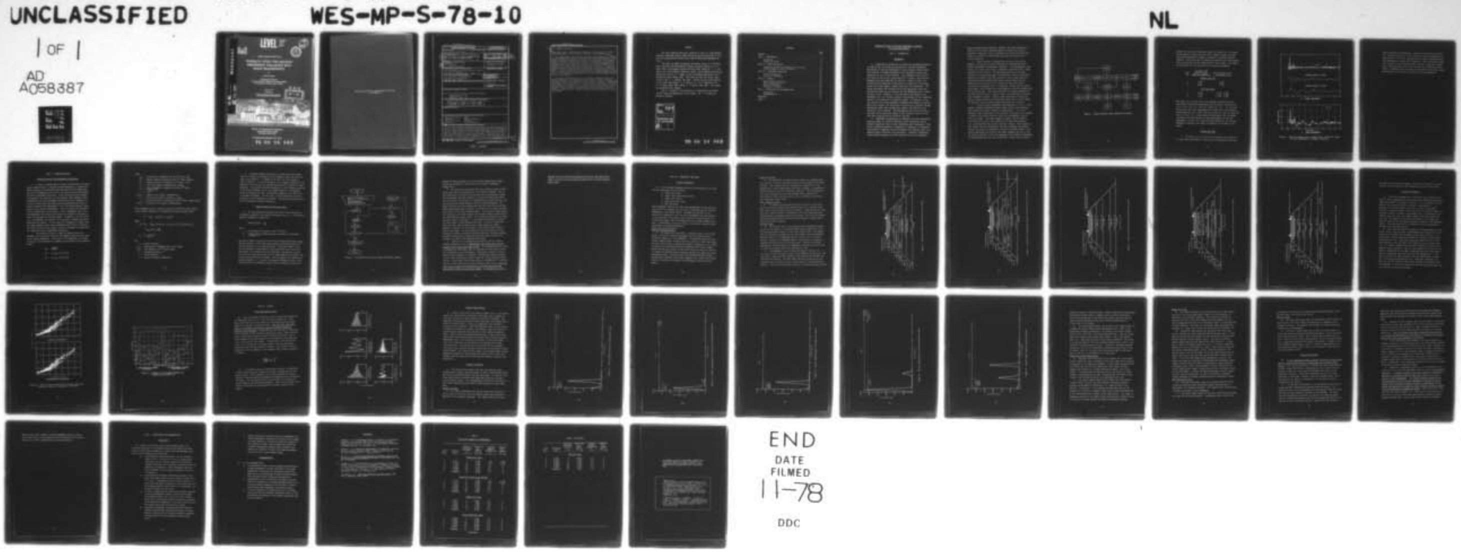

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FEASIBILITY STUDY FOR RAILROAD EMBANKMENT EVALUATION WITH RADAR MEASUREMENTS

by

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A study was conducted to determine the feasibility of using radar measurements to define railroad embankment subsurface layer thickness and properties. A computer model was used to calculate radar reflectances as could be measured over the frequency range of 0.5 to 2.0 GHz at the surface of five different railroad embankments for which data were available. These reflectance curves were converted to realistic depth displays as could be obtained from a real-time analysis of swept-frequency radar data or from a more conventional narrow-

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pulse radar system. Comparisons were then made of the results of the radar system measurements with the physical conditions of the embankments.

The results support the feasibility of using radar measurements to define railroad embankment properties and indicate that surface and subsurface reflectance components can be separated on the basis of characteristic interference patterns and used to estimate the properties of layered media. Interface reflections from the bottom of ballast materials in railroad embankments should be detected with radar measurements whenever (as in the case of the five embankments used in this study) there is significant contrast in the electrical properties of the ballast materials and the material upon which the ballast is placed. Interfaces between layered materials with high water contents beneath ballast material may be difficult to detect from the radar measurements over the 0.5- to 2.0-GHz frequency range because of the high attenuation rates for radar waves in such materials.

Detection of artificial interfaces in railroad foundations should be possible by analyzing radar reflectance data in a manner similar to that for embankment materials. For example, high water tables or cavities in embankments will produce large reflectance values in the subsurface components of the radar measurements. In a similar fashion, during the construction phase of the railroad embankments, artificial layers or targets (such as metal sheets) could be placed at regular intervals in embankments so that during later periods the movements of these artificial layers or targets could be interpreted as foundation movement.

PREFACE

The study reported herein was conducted at the U. S. Army Engineer Waterways Experiment Station (WES) during the period January-March 1978 for the Transportation Systems Center under Reimbursable Agreement No. 76-41.

The study was under the general supervision of Mr. W. G. Shockley, Chief, Mobility and Environmental Systems Laboratory (MESL); Mr. B. O. Benn, Chief, Environmental Systems Division (ESD), MESL; Mr. J. P. Sale, Chief, Soils and Pavements Laboratory (S&PL), now designated Geotechnical Laboratory; and Dr. P. F. Hadala, Chief, Earthquake Engineering and Vibrations Division (EEVD), S&PL. The study was under the direct supervision of Mr. J. L. Lundien, ESD, MESL. Persons actively participating in this study were Messrs. R. F. Ballard, Jr., R. H. Ledbetter, and S. S. Cooper, EEVD, S&PL; and Mr. E. A. Baylot, ESD, MESL. This report was prepared by Mr. Lundien.

COL J. L. Cannon, CE, was Director of the WES during the conduct of this study and preparation of this report. Mr. F. R. Brown was Technical Director.

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FEASIBILITY STUDY FOR RAILROAD EMBANKMENT EVALUATION WITH RADAR MEASUREMENTS

PART I: INTRODUCTION

Background

1. Quantitative information on surface and subsurface materials is required for the design and evaluation of railroad embankments. Maintenance of railroad embankments to insure adequate safety levels also requires a thorough knowledge of the subsurface thickness and properties of soil or rock involved. This information may be quite well known at the initial construction phase; however, once these embankments have been completed and used for a number of years, the thicknesses and properties of the materials change due to the normal action of the environment, loading conditions, and maintenance. The design thicknesses and strengths which were appropriate during the construction phase may not describe the same embankment after a number of years of use. Obviously, if one can monitor the changes in an embankment over its lifetime, potential displacements or even impending failure can be predicted as conditions change. In addition, if one can identify areas where embankment strengths have changed or displacements have occurred, the deficiencies can usually be corrected through maintenance rather than through major repairs, and potential cost reductions can be achieved. Even maintenance costs can be reduced if bad spots can be accurately marked so that corrective action is only used where required and not for entire sections.

2. Embankment displacements or subsurface structure deformation requiring repair are usually detected by field observation during periodic inspection trips or while performing other maintenance. Much of the information gathered by inspection is supported by information from probing or augering into the foundation with sampling tools or by comparing grade elevations with bench marks. Generally, maintenance records provide guidance for major corrective action on embankments

where long sections are involved. However, the above observations usually are of surface conditions and do not define the specific subsurface conditions, such as thicknesses of ballast and underlying layers, or location of water pockets and zones of high moisture content materials.

3. Several systems, including both mechanical and electromagnetic, may be used to make nondestructive investigations which provide information on embankment conditions. An electromagnetic wave system (i.e. radar) also offers a noncontact operational mode. Other advantages are as follows: the operating frequency of the radar system can be selected for depth of penetration control; radar can be operated at extremely high data acquisition rates, making possible subsurface profiling measurements from a moving vehicle; and the search area can be controlled by varying the beam width of the projected electromagnetic wave. In addition, systems with low power requirements can be constructed using components available commercially at the present time. Radar wave reflection is strongly dependent on the water content of soils, and the results can show good correlation with embankment strength. Finally, radar subsurface profiling can greatly minimize the need for extensive borings and will often define the specific locations where borings and samples are necessary.

4. Previous radar measurements have been made at the U. S. Army Engineer Waterways Experiment Station (WES) using a swept-frequency radar system for highway foundation investigations.[1] The swept-frequency radar system used in this previous investigation was designed to measure reflectance from test sites over the frequency range of 0.25 to 8.00 GHz. The system (Figure 1), which could be moved by truck from site to site, was composed of two major subassemblies, i.e. the transmitter and receiver sections. However, this system was much larger than that required for railroad embankment measurements because the system was designed to simulate an airborne system. When ground measurements are desired, the radar equipment and the size of the vehicle required to carry the equipment can be reduced considerably. The measurements made with this system were a series of interference

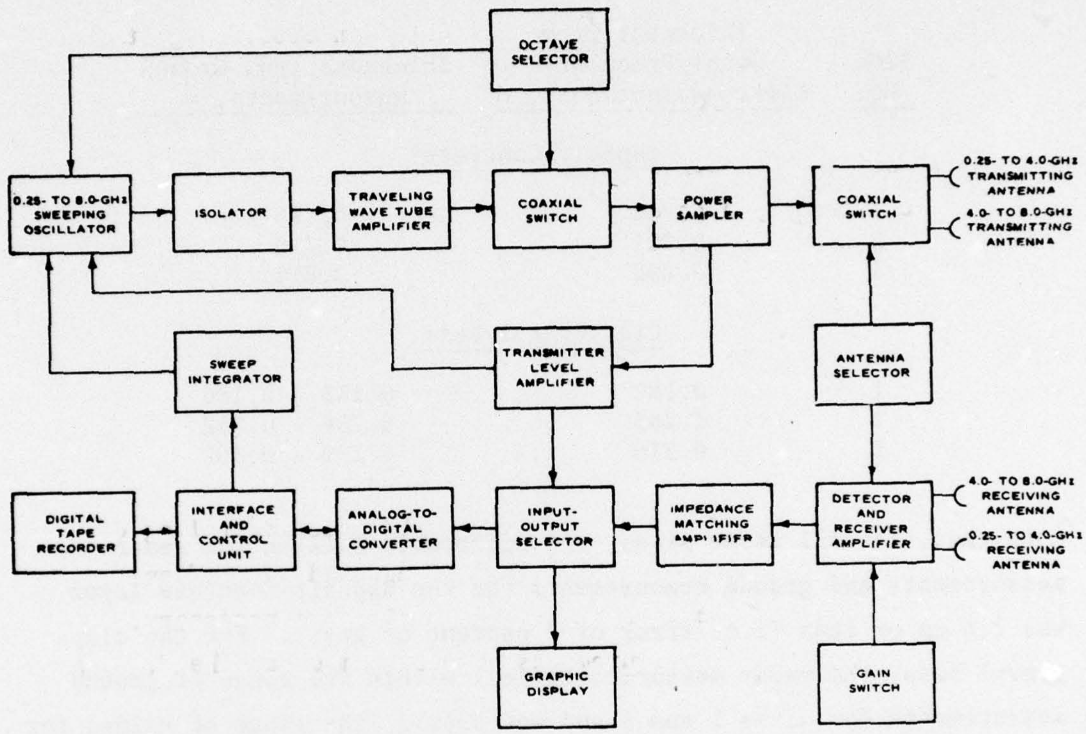

Figure 1. Swept-frequency radar system block diagram

patterns in the power reflectance curves (see Figure 2b). By using a simple analysis concept where the cyclic patterns (Figure 2a) were extracted automatically, depths to subsurface interfaces could be computed. Shown below are the predicted thicknesses for three highway sites as measured with the swept-frequency radar system. Also shown for comparison are the thicknesses from ground measurements.

Site No.	Thickness from Swept-Frequency Radar Measurements, m	Thickness from Ground Measurements, m
	Asphalt Concrete	
1	0.242	0.226
2	0.221	0.210
3	0.202	0.214
	Clay-Gravel Base	
1	0.182	0.133 - 0.186
2	0.263	0.209 - 0.262
3	0.310	0.309 - 0.362

Note that, for all three sites, the difference between the radar measurements and ground measurements for the asphalt concrete layer was 1.6 cm or less (i.e. error of 7 percent or less). For the clay-gravel base, the radar measurements fell within the range of ground measurements for sites 1 and 3 and was outside the range of values for site 2 by only 1 mm. Similar depths of penetration and measurement accuracies could be expected for radar measurements on railraod embankments. Results of a study to define feasibility for railroad embankment evaluation with radar are presented in the body of this report.

Purpose and Scope

5. The purpose of this study was to determine the feasibility of using radar measurements to define railroad embankment subsurface

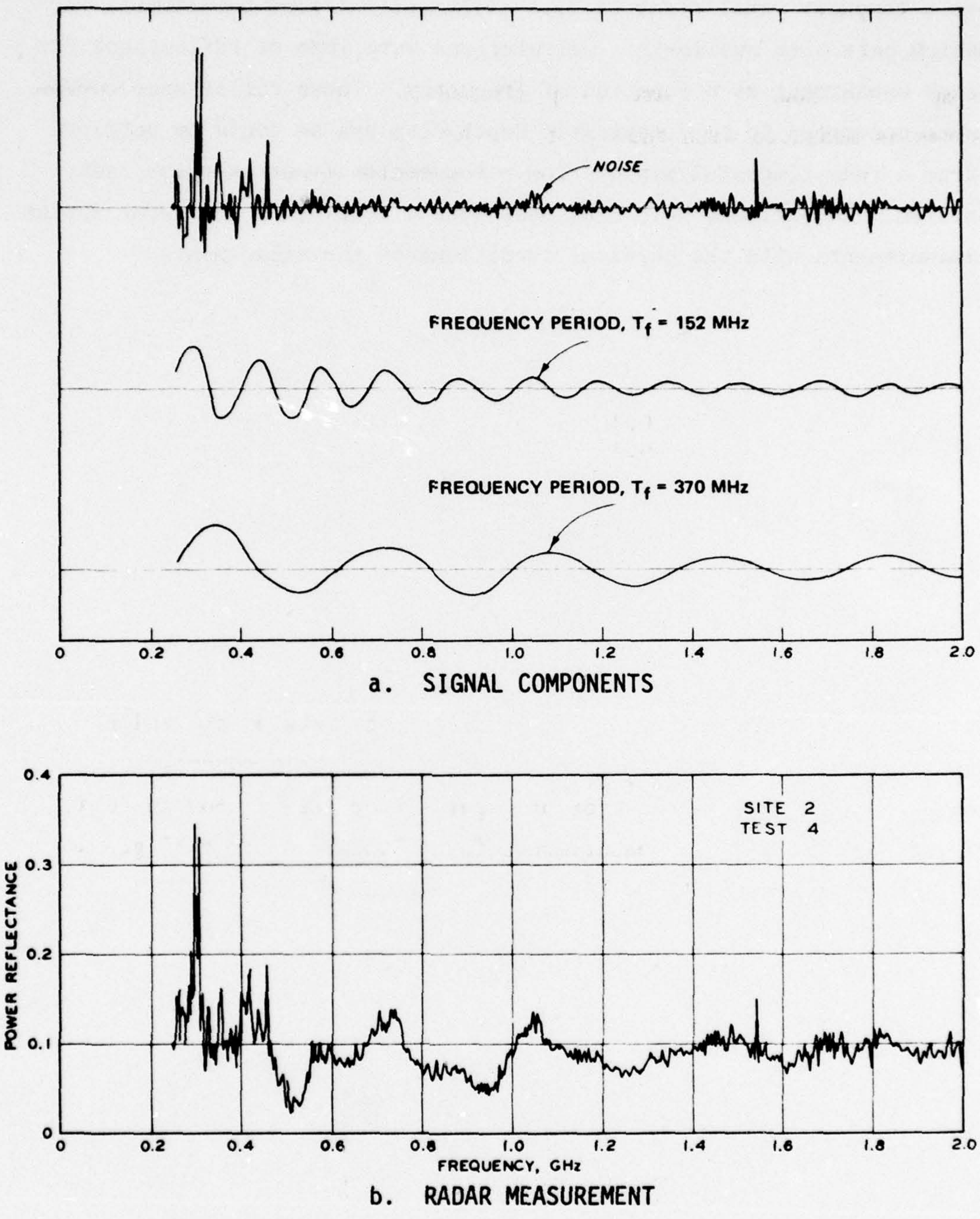

Figure 2. Separate components and combined power reflectance signal for radar measurement of highway foundation

layer thicknesses and properties. The scope of the work was limited to a computer model study of five different railroad embankments for which data were available. Calculations were made of reflectance for each embankment as a function of frequency. These reflectance curves were converted to very realistic depth displays as could be obtained from a real-time analysis or from a conventional narrow-pulse radar system. Comparisons were then made of the results of the radar system measurements with the physical conditions of the embankments.

PART II: SIMULATION MODELS

Theoretical Model for Reflectance Calculations

6. In order to generate data to study the feasibility for using swept-frequency radar to evaluate railroad embankments, a theoretical model developed at the USAE Waterways Experiment Station (WES) based on plane-wave propagation was used to calculate the power reflectance for various embankment conditions. These calculations were designed to demonstrate the sensitivity of the proposed swept-frequency radar measurements to various embankment conditions and were generated in a realistic fashion such that they would be approximately the same as would be expected from measurements with a real swept-frequency radar system on real railroad embankments. Layer interfaces were assumed to be flat and parallel to the surface. This is appropriate for a railroad embankment when antenna beam widths are selected to look only at small areas between the railroad tracks. In addition, the last layer (i.e. the subgrade) was assumed to be very deep in comparison with the operating wave lengths. In most cases this assumption is proper since the swept-frequency radar system transmitted power would be limited to very small values and thus signals could only propagate to depths that are compatible with the embankment thicknesses.

7. The theoretical effort is based on complex electrical impedances of the various dielectric and magnetic materials which make up the layered embankment. Each layer in the embankment was assumed to have its own characteristic impedance as calculated by the equation below:[2]

$$Z_{on} = \sqrt{\mu_n^*/\epsilon_n^*}$$

$$\mu_n^* = \mu_o \mu_{rn} (1-j \tan \delta_m)$$

$$\epsilon_n^* = \epsilon_o \epsilon_{rn} (1-j \tan \delta_d)$$

where

Z_{on} = characteristic impedance for the n^{th} layer, ohms

μ_n^* = complex magnetic permeability for n^{th} layer, Henry/m

ε_n^* = complex dielectric constant for n^{th} layer, Farad

μ_o = free space magnetic permeability, Henry/m

μ_{rn} = relative magnetic permeability for the n^{th} layer, dimensionless

j = $\sqrt{-1}$

$\tan \delta_m$ = magnetic loss tangent, dimensionless

ε_o = free space dielectric constant, Farad/m

ε_{rn} = relative dielectric constant for the n^{th} layer, dimensionless

$\tan \delta_d$ = dielectric loss tangent, dimensionless

These impedances cause a change in the power reflection at the surface of the layered embankment as computed by the equation shown below:

$$R = \left|(Z_{L1} - Z_{air})/(Z_{L1} + Z_{air})\right|^2$$

where

$$Z_{Ln} = Z_{on} \left\{[Z_{Ln+1}\cos(\gamma_n \ell_n) + Z_{on}\sin(\gamma_n \ell_n)]/[Z_{on}\cos(\gamma_n \ell_n) + Z_{Ln+1}\sin(\gamma_n \ell_n)]\right\}$$

$$\gamma_n = j\omega \sqrt{\varepsilon_n^* \mu_n^*}$$

and

R = power reflectance

Z_{air} = characteristic impedance for air (377 ohms)

Z_{Ln} = load impedance for n^{th} layer, ohms

γ = propagation factor, m^{-1}

ℓ = layer thickness, m

ω = angular frequency, radians/sec

8. A computer program was written to compute the power reflection as a function of frequency for the frequency range over which the radar system operates. A condensed flow chart for this program is shown in Figure 3. In the first step for this computer program, all the input data for each layer are defined along with the controls for radar operation. The program calculates impedances at each interface starting at the lowest frequency and for the deepest material. The program cycles up through each layer, transforming impedances as it goes until it reaches the surface. At that point, a power reflectance is calculated and the next frequency is selected. The operation continues until all the frequencies have been exhausted.

Computer Model for Data Processing

9. The data processing procedure was based on the detection of interference patterns in the power reflectance curves, i.e., the optical depth was computed as shown below.

$$\text{Optical Depth} = \frac{c}{2T_f}$$

where

c = free-space wave velocity, 300×10^6 m/sec

T_f = period between adjacent maxima or minima on interference pattern, Hz

The optical depth is defined as the distance between reflecting surfaces which if present in free space would produce interference patterns of the sane period as in the layered medium. The optical depth in turn can be converted to true depth by correcting for the wave velocity in the medium. For relatively low loss materials, the decrease in wave velocity over free-space velocity can be approximated by the square root of the relative dielectric constant. One can measure the interference patterns manually, i.e. measure the frequency difference between interference maxima or interference minima from the reflectance curves and

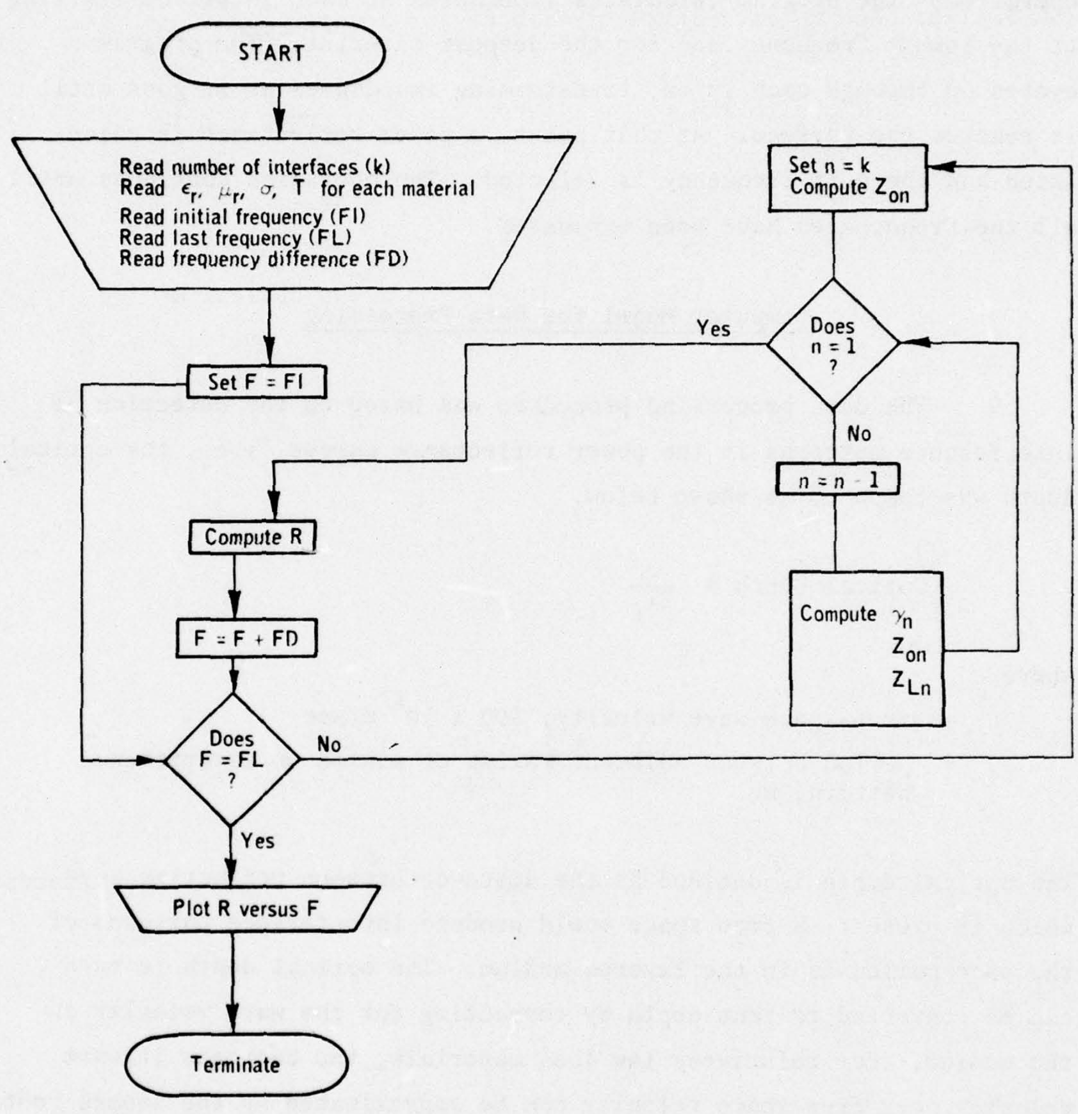

Figure 3. Condensed flow chart for radar reflectance program

compute the optical depth, or one can use more sophisticated signal processing techniques to extract the cyclic pattern information automatically.

10. One method for extracting the cyclic pattern in power reflectance signal data is through the use of a Fourier transform. This is the method used to extract the cyclic data for this feasibility study. For this method, the mean reflectance is subtracted from each reflectance data point, the results are transformed by a window function, and the data are then passed through a Fourier transform program. The window function used in processing data for this study was the minimum three-term Blackman-Harris window.[3] Its purpose was to reduce the side-lobe content in the optical depth display. In the optical depth display, the locations of the peaks indicate the interface depths as detected by the swept-frequency radar system. If the interface reflection is large, one would expect a large peak. If the interface reflection is small, one would expect a corresponding small peak. Because of distortions which can arise from the reflection of radar signals at complex boundaries, there can be false peaks in the optical depth display as well as real peaks. In the evaluation of the radar results, it was necessary to define an operating criterion that the real peaks marking interface reflections be larger than the false peaks caused by the distortion of some of the interface reflections.

11. Another way of interpreting the results from the Fourier transform program is that it approximates the results that could be obtained from a short pulse radar system. The windowing function serves to modulate the reflectance data in a pattern such that when the data are transformed to the time domain, a reflectance, delayed in time at each interface boundary, is obtained. Although the results presented in this report specifically refer to that for a swept-frequency radar systems, a short pulse radar system should be considered as a candidate for field tests along with the swept-frequency radar system. Note that other radar systems can be simulated by using the same processing procedure and different processing windows. This becomes one of the

powerful tools in the modeling program in that the same model can be used as an aid in the data reduction required for an actual operating radar system.

PART III: EMBANKMENT CONDITIONS

Physical Properties

12. Five railroad embankment profiles were selected as test cases for the feasibility study as follows:

a. Kansas Test Track.

b. Kansas Test Track-fouled ballast.

c. Pueblo Test Track.

d. Rock Island Test Track.

e. WES Test Track.

These embankment profiles are taken from measurements of real profiles and are felt to represent typical cases of both good and poor railroad embankments in the United States. Although these profiles do not represent an exhaustive cross section of embankments that are possible, it was felt that if the radar system operated on these profiles in a satisfactory manner, they could handle many of the other conditions as well. A description of the test tracks is given below along with their performance as railroad embankments.

Kansas Test Track and Kansas Test Track-fouled ballast

13. The Kansas Test Track (KTT), a research facility near Aikman, Kansas, was used to evaluate performance for nine different track structures founded on a clay embankment. The material properties used in both examples refer to Kansas Test Track section 9, which used wooden crossties and was built to approximate Santa Fe standards for the region. The Kansas Test Track-fouled ballast enbankment profile had a higher density and moisture content in the ballast material under the crossties (to simulate a fouled ballast situation) than does the Kansas Test Track enbankment profile. The Kansas Test Track experienced early failure through water softening of the upper subgrade clay. Hence, both example cases are considered to represent poor performance conditions under traffic.

Pueblo Test Track

14. The Department of Transportation operates the Transportation Test Center Facility for Accelerated Service Testing (FAST) near Pueblo, Colorado. This example, based on representative properties of the predominantly sandy Transportation Test Center roadbed, is considered to represent good to excellent foundation conditions. The Transportation Test Center subgrade has posed few problems under conditions of accelerated testing, and this example case is considered to represent good performance under traffic.

Rock Island Test Track

15. The Federal Railroad Administration sponsored a lime-slurry pressure injection stabilization research project on a section of the Rock Island railroad track in eastern Arkansas. Conditions of the track were poor, which resulted in uneconomical, slow-speed operations and required weekly maintenance along some sections. The track has unstable conditions resulting from uneven ballast distribution, trapped water, and a weak plastic subgrade.

WES Test Track

16. The WES Test Track is sponsored by the Transportation System Center for the purpose of evaluating nondestructive geophysical tools for detecting change caused by lime-slurry stabilization. The embankment was designed to simulate an old, low-strength railroad embankment. Material layers in the embankment consist of clean ballast, fouled ballast to simulate old degraded ballast, clayey gravel to simulate a subgrade and ballast mixture, and lean clays. Moisture and density measurements were made during the embankment construction and were used to define the profile used in this feasibility study.

17. The embankment cross sections are shown in Figures 4-9. In all cases, five or six layers on top of the subgrade are indicated. The top layer is defined by the thickness of the crosstie and includes the clean ballast material. The next layer consisted of ballast material (crushed stone or slag) mixed with a small amount of fine-grained soil material. The rest of the layers were soils at various moisture contents

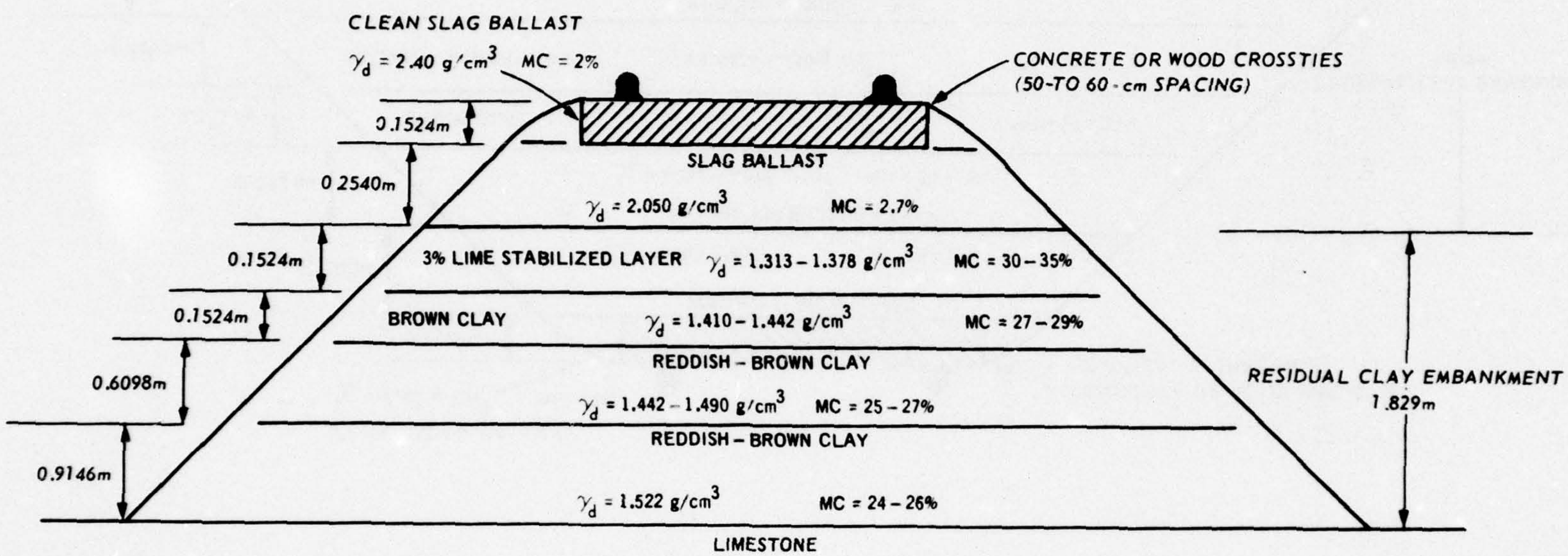

Figure 4. Kansas Test Track cross section (not to scale)

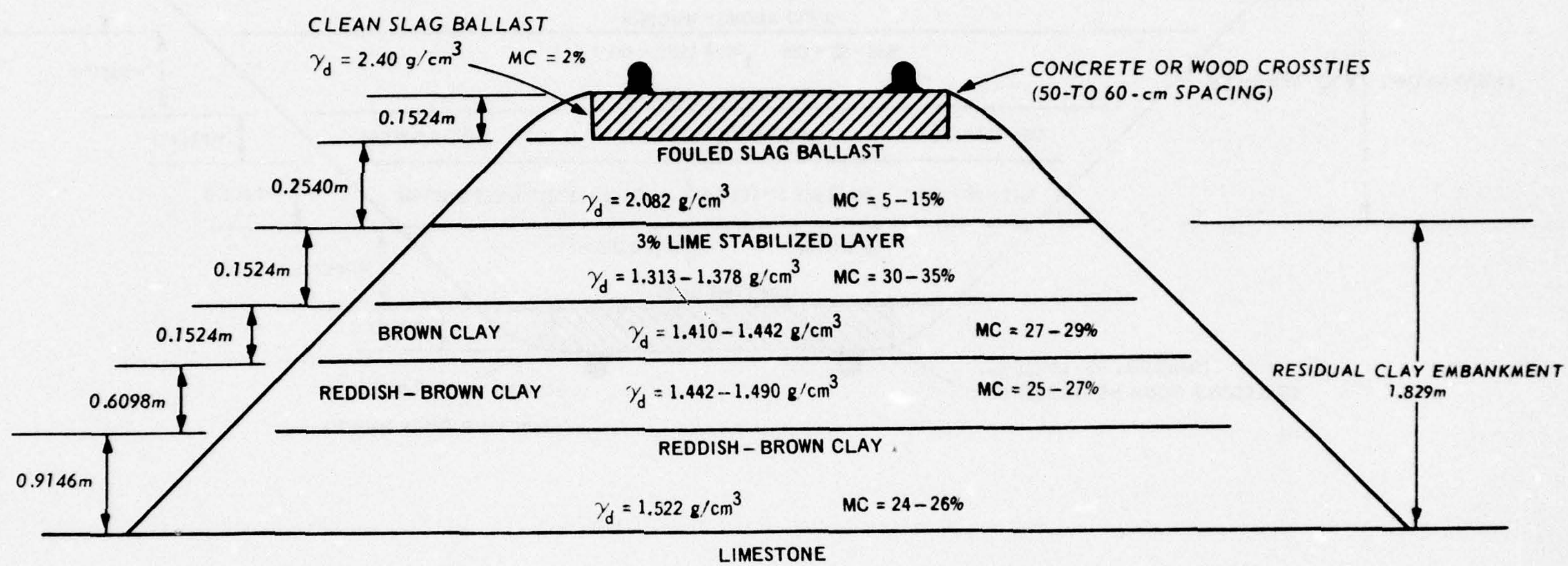

Figure 5. Kansas Test Track-fouled ballast cross section (not to scale)

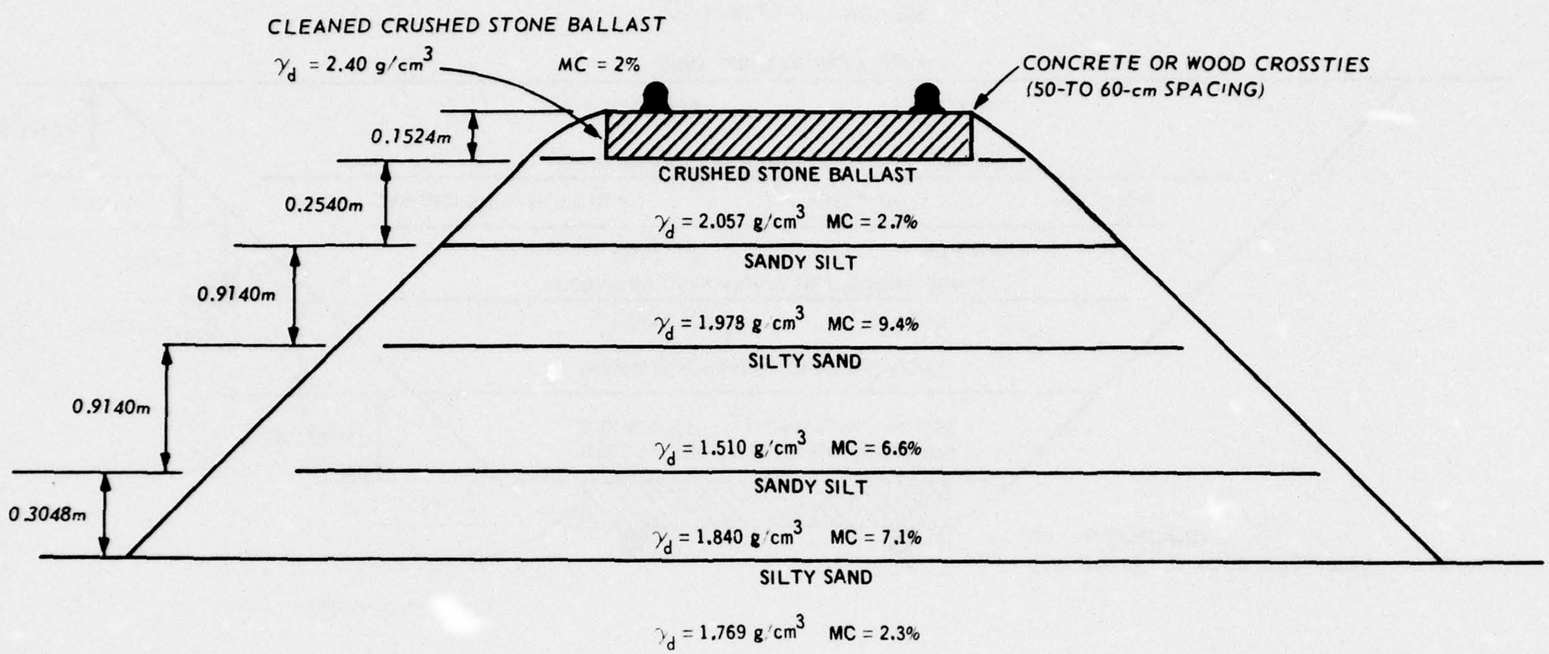

Figure 6. Pueblo Test Track cross section (not to scale)

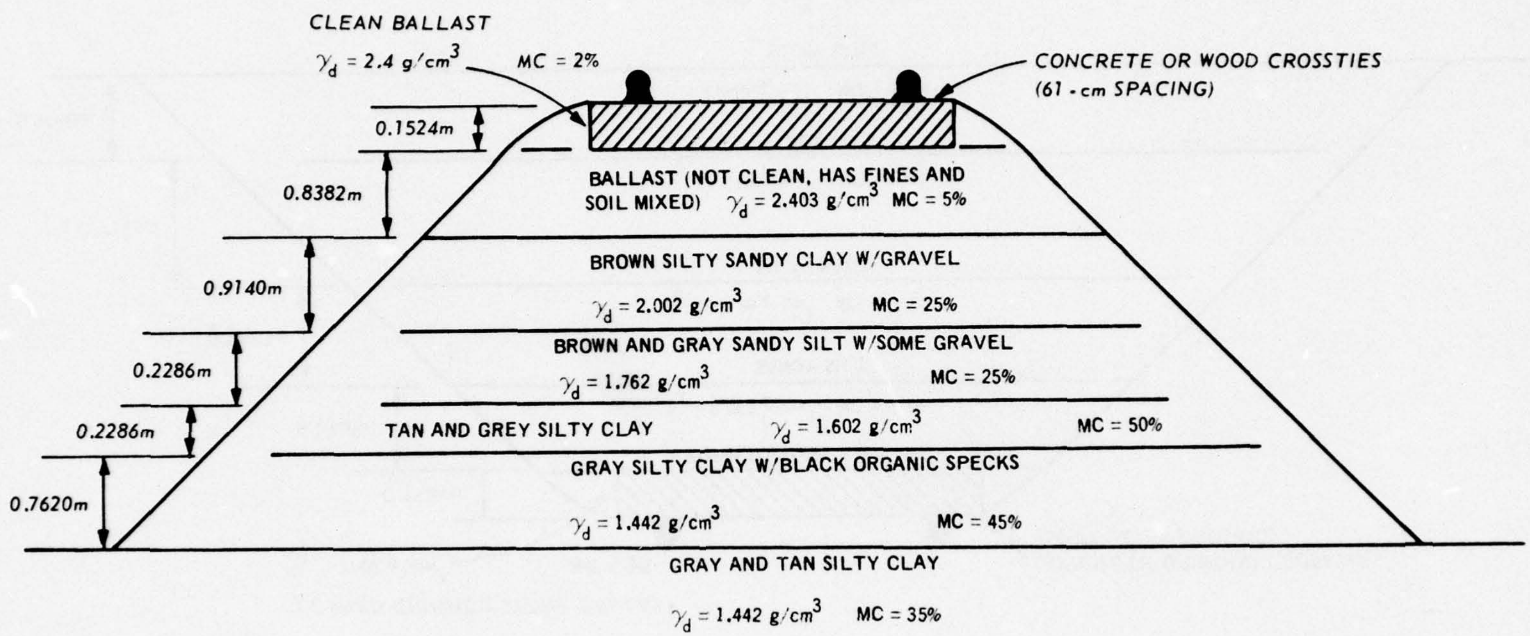

Figure 7. Rock Island Test Track cross section (not to scale)

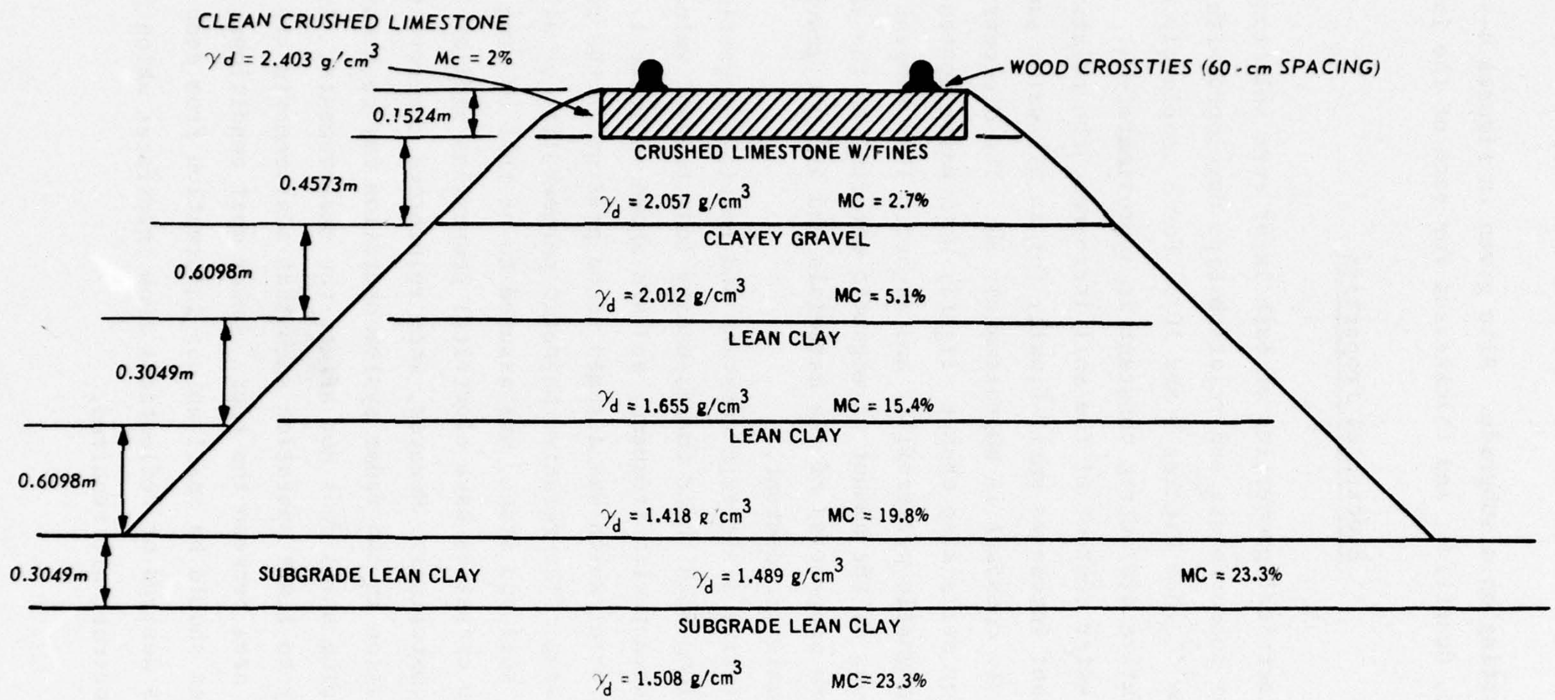

Figure 8. WES Test Track cross section (not to scale)

and densities resting on a subgrade. Also given in Figures 4-9 are the moisture content, densities, and thicknesses for each of the layers.

Electrical Properties

18. The electrical properties of each layer were selected on the basis of previous measurements and relationships developed with moisture content by volume[4,5] (see Figures 9 and 10). For a completely dry soil material the relative dielectric constant is approximately 4. In general, as the water content of the soil increases, the relative dielectric constant increases until finally for an all-water sample, the relative dielectric constant is approximately 80. The dielectric loss tangent values for soils also change slightly with water content and soil type. The magnetic permeability and magnetic loss tangent are primarily functions of the amount of magnetic material in the embankment layers. These are properties of the materials and are not generally affected by the moisture content.

19. The relative dielectric constant and relative magnetic permeability values, along with their corresponding loss tangent values, were assumed to be constant with frequency and are shown in Table 1. The only magnetic material which was assumed to be present in the railroad foundations was slag. The relative magnetic permeability of all the other materials, soil and stone, was assumed to be that of free space, i.e. 1.0. Wooden crossties have electrical properties similar to non-magnetic ballast materials. However, when reinforced concrete ties are present, modification in the radar system operation may be necessary so that the reinforcing steel does not affect the measurements. It may then be necessary to limit operation such that measurements are taken only in the open area between the ties. Under most conditions, the effect of the ties should be small unless information from deep within the embankment is desired or reflections from interfaces which have very low electrical contrast are required.

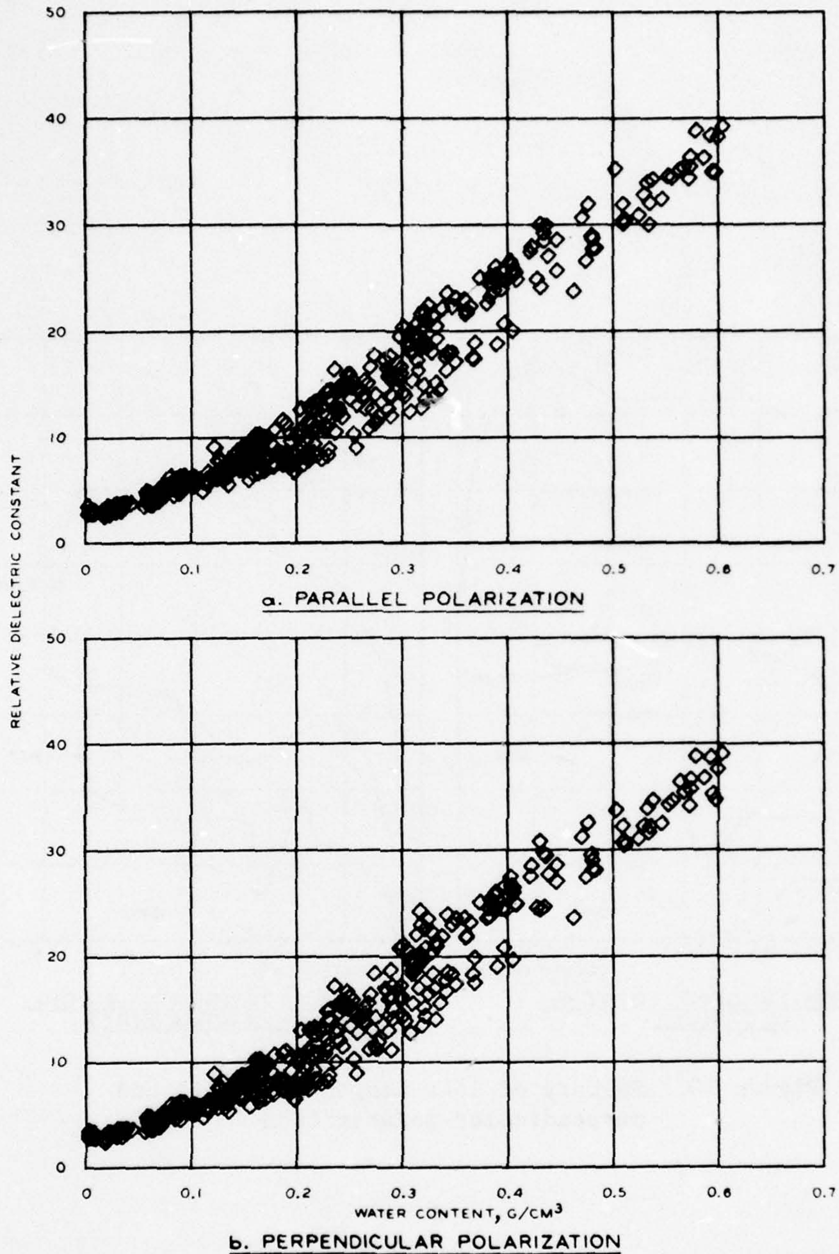

Figure 9. Effect of water content on the relative dielectric constant of soils at a frequency of 1.074 GHz

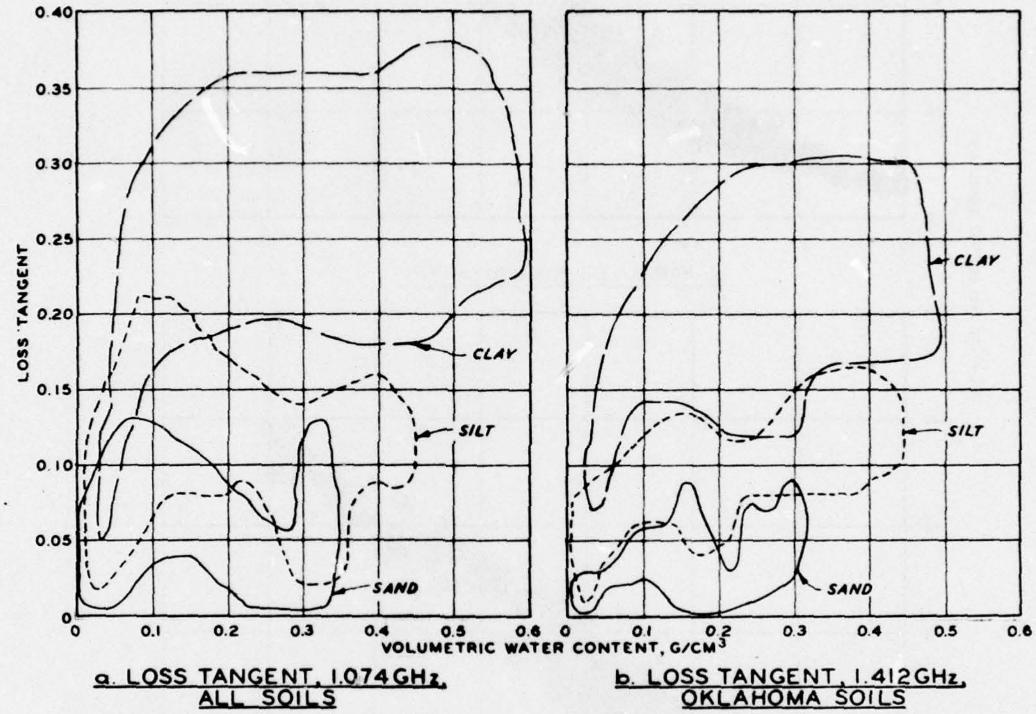

Figure 10. Summary of loss tangent parallel and perpendicular polarization

PART IV: RESULTS

Power Reflectance Results

20. Power reflectance curves for each of the railroad foundations for frequencies from 0.5 to 2.0 GHz are shown in Figure 11. These power reflectance curves are composed of interference patterns superimposed on a constant reflectance value. Note that each reflectance pattern is different and therefore suggests different foundation materials and thicknesses. Reflectance at each interface is controlled by the contrasts in the electrical properties; however, these relationships are modified by depth such that the reflections which occur at deeper depths can be much reduced by the attenuation of the radar wave as it travels back to the surface. The mean value of the reflectance curves (i.e. the constant reflectance value) gives the approximate reflectance from the top or ballast material. The relative dielectric constant of this top material can be computed from a simple expression as follows:

$$\varepsilon_r = \left(\frac{\sqrt{R} + 1}{\sqrt{R} - 1} \right)^2$$

21. In a fashion similar to that in the top layer, the amplitude of the oscillations gives indication of signal strength from the subsurface layers. These amplitudes can also be converted to relative dielectric constants provided additional information on wave attenuation is present. The period of oscillation can be used to calculate the optical depth to the reflecting interface. Again, the true depth can be found by correcting the optical depth by the wave velocity in the medium.

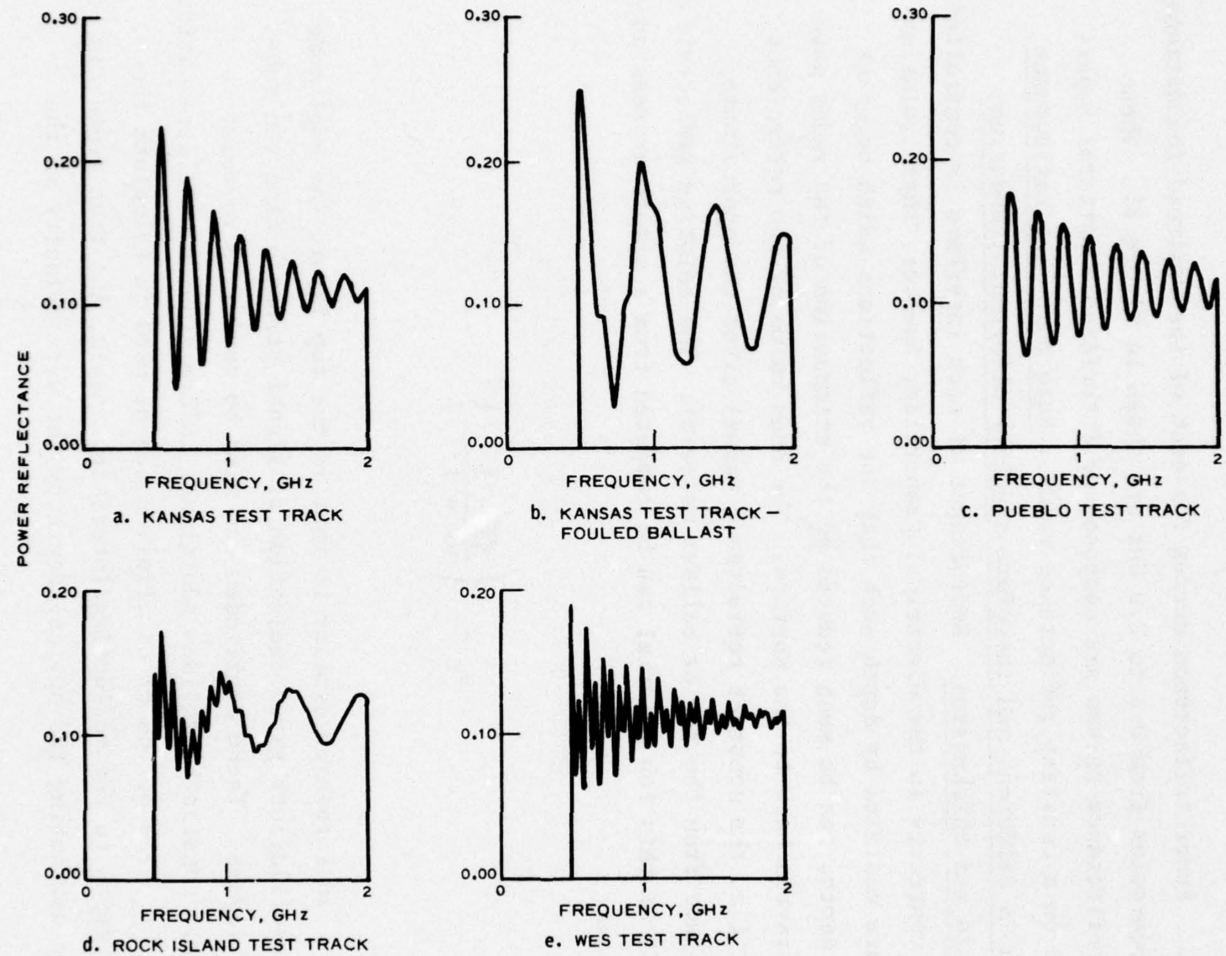

Figure 11. Power reflectance curves for railroad foundations

Optical Depth Results

22. Optical depth curves are shown in Figures 12-16. In all these curves, the oscillations of the power reflectance curves (Figure 11) have been converted to optical depth via the Fourier transform. The amplitude of the peaks gives the relative amplitude of the power reflectance oscillations which, in turn, are dependent on the electrical contrast of the interfaces. There are additional peaks to those caused by interface reflections in some of the displays, which are caused by processing data that have been distorted in the complex propagation paths. Some of these extra peaks are equivalent to those of an actual pulsed radar system where multiple reflections have occurred within the embankment itself. The locations of the peaks on the optical depth scale are an indication of the period of oscillation of the power reflectance data. The shorter periods of oscillation in the power reflectance curve indicate interface reflections are occurring at deeper optical depths. Also shown on these curves is the optical depth of each embankment interface as obtained from the product of the actual layer thickness and the square root of the relative dielectric constant (see paragraph 9).

Analysis of Results

23. The criterion for analysis was that true interface peaks should always be larger than false peaks, or that a simple method should be used to discriminate between true and false peaks. In addition, true peaks should always be present when significant electrical contrast occurred between layers. All interpretations should be on the basis of very simple expressions which could be easily applied to actual radar data.

Kansas Test Track

24. The power reflectance curve for the Kansas Test Track (Figure 11a) shows a relatively clean oscillating signal which decreases in amplitude as the frequency increases. This suggests that most of the

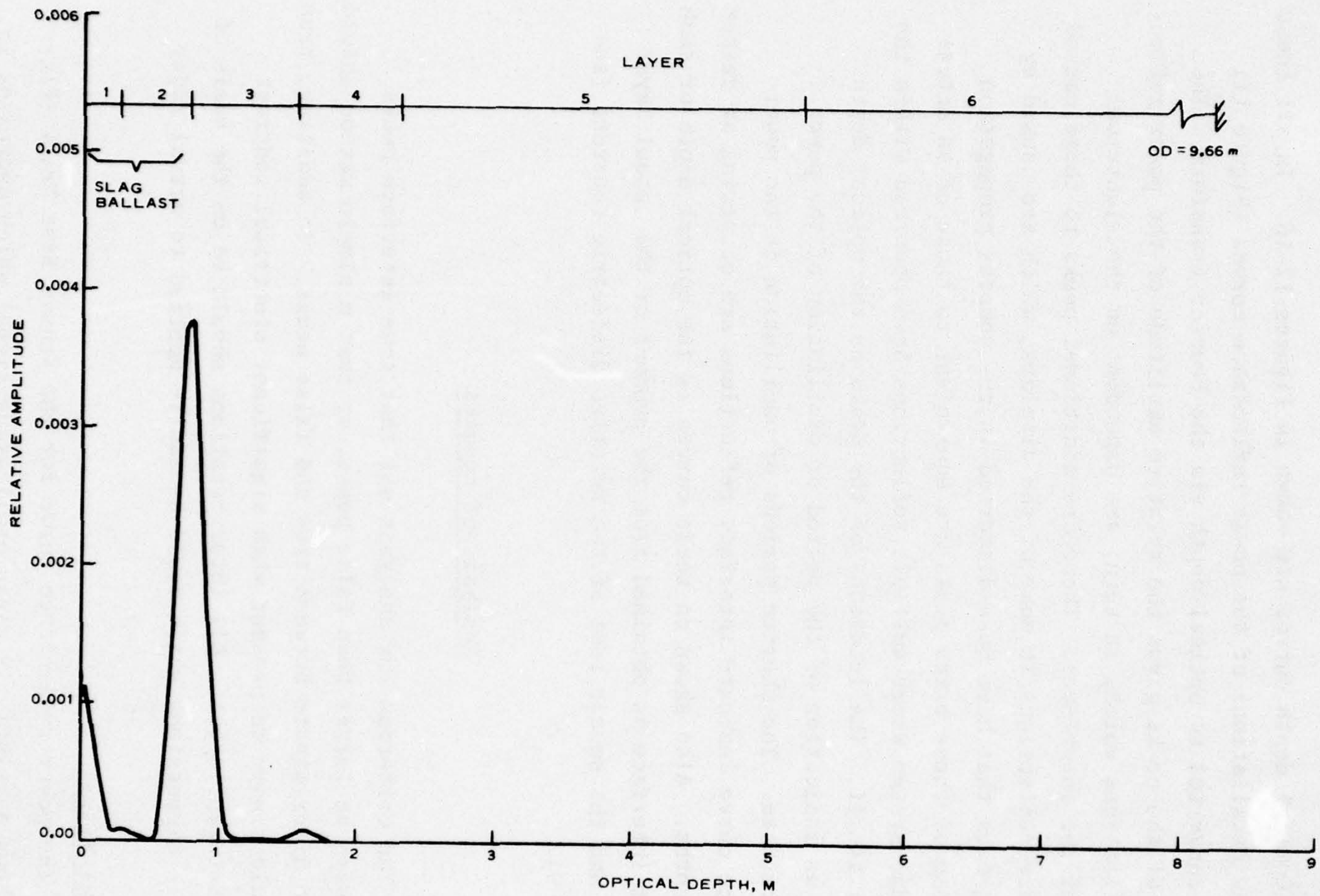

Figure 12. Optical depth display for Kansas Test Track

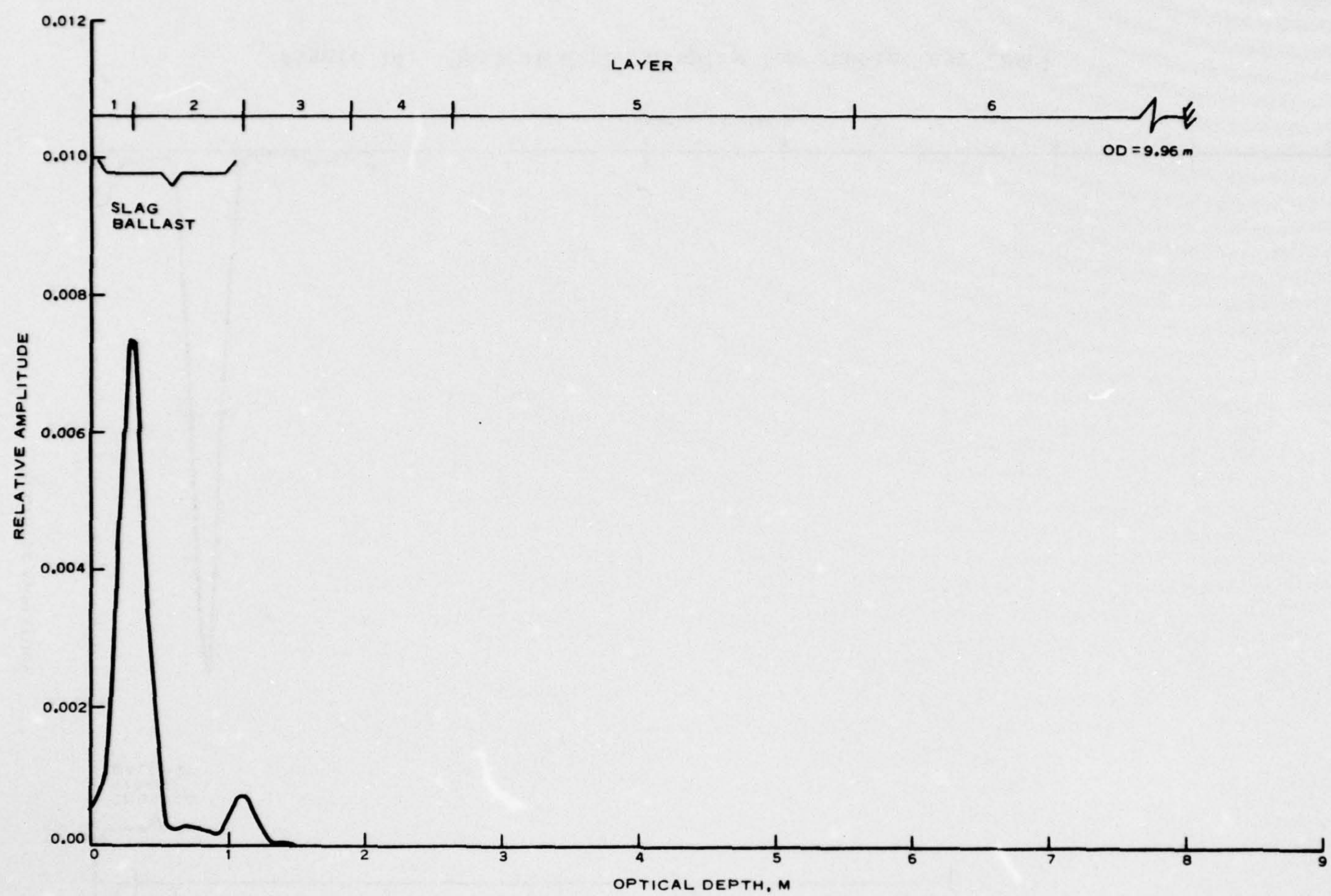

Figure 13. Optical depth display for Kansas Test Track-fouled ballast

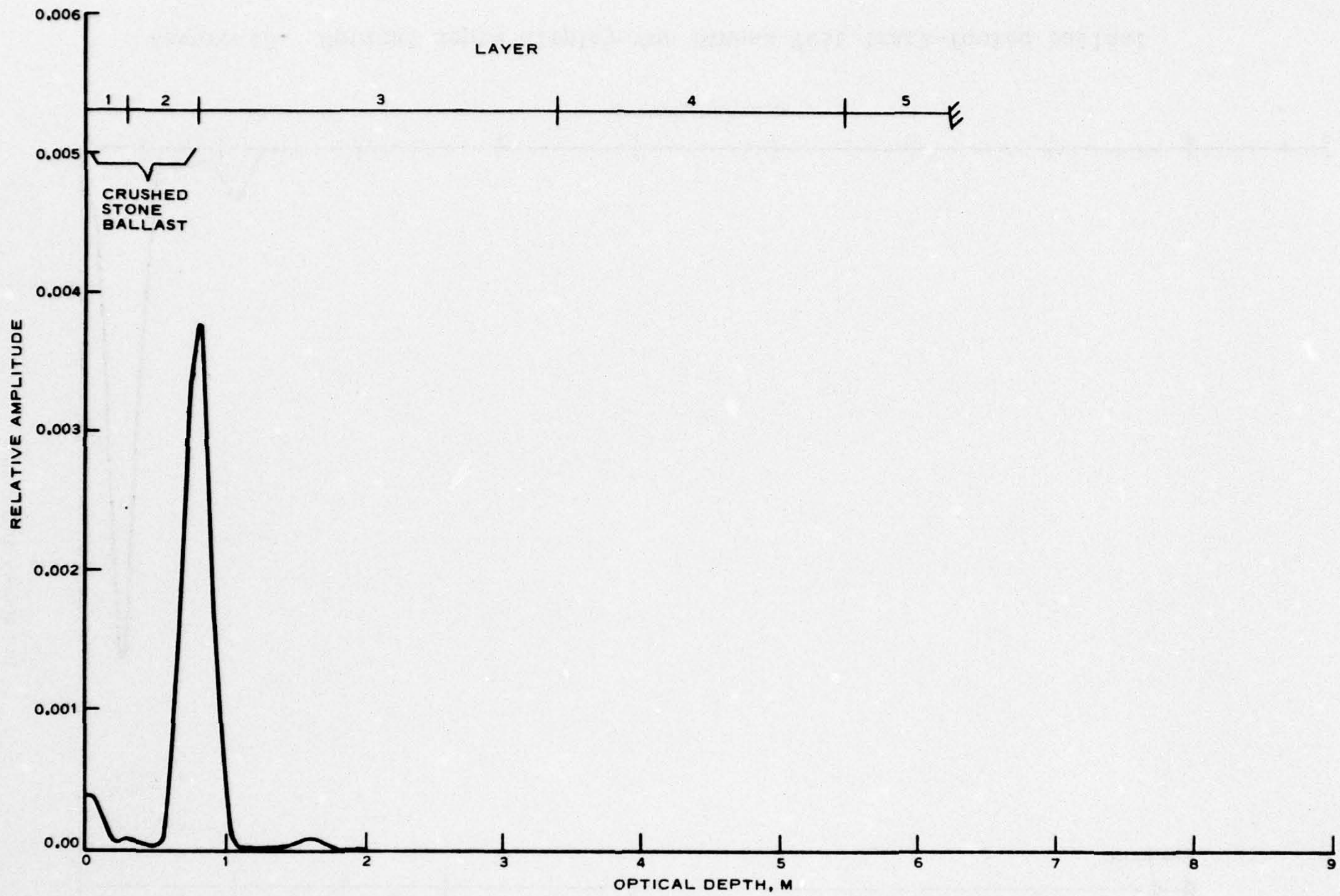

Figure 14. Optical depth display for Pueblo Test Track

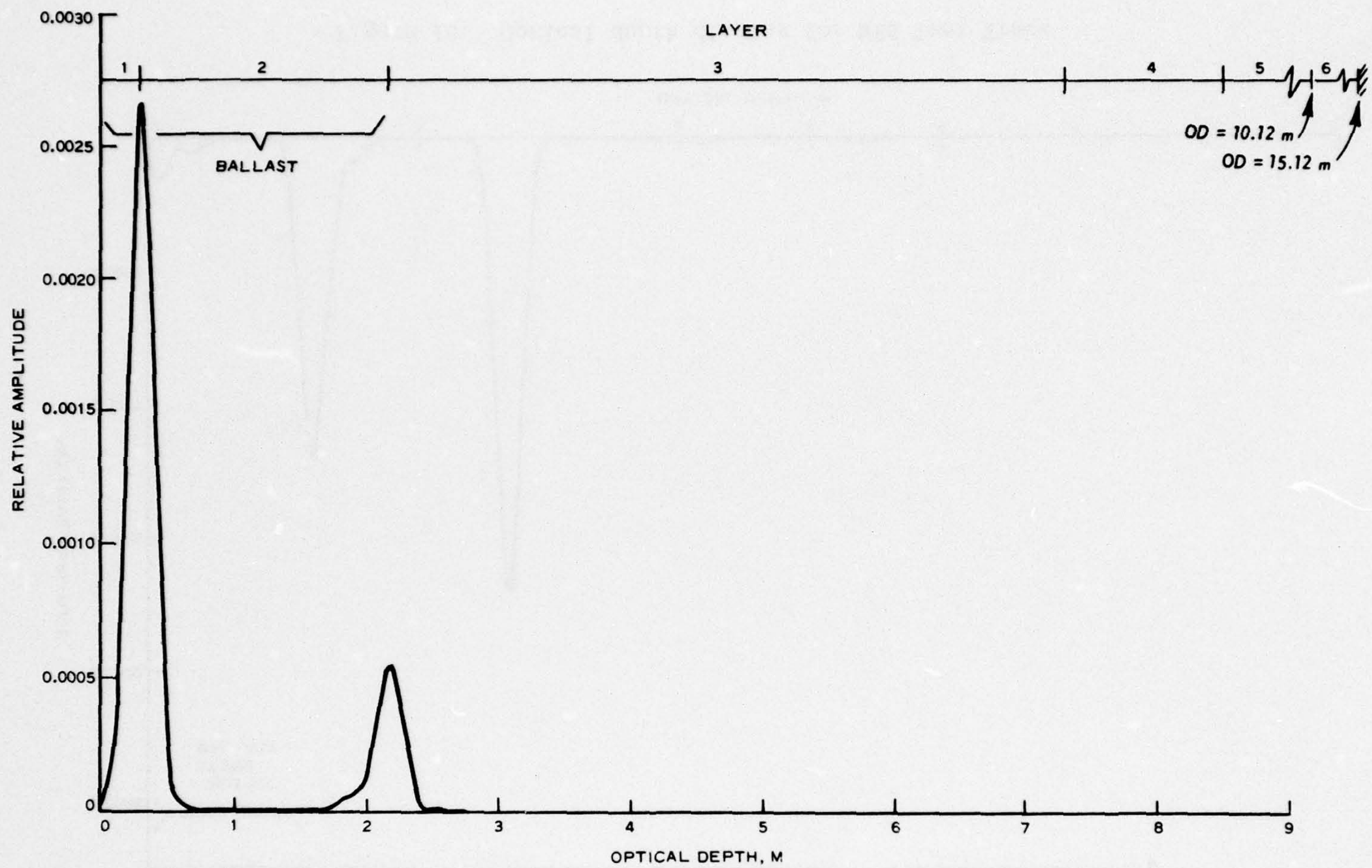

Figure 15. Optical depth display for Rock Island Test Track

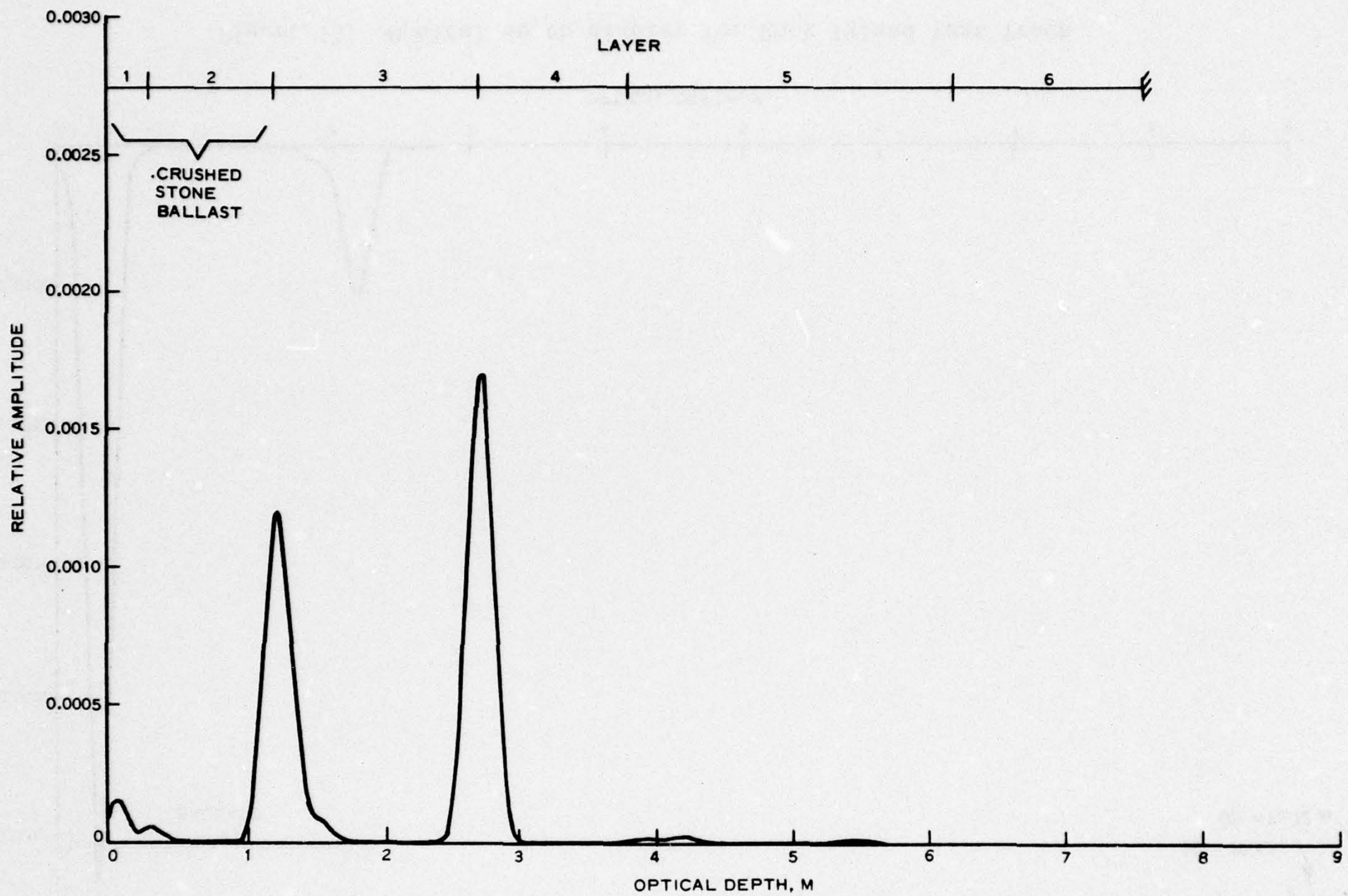

Figure 16. Optical depth display for WES Test Track

subsurface energy is reflecting from a single interface and is generating interference patterns when it combines with the surface reflectance. The decreasing amplitude of the oscillating signal indicates that the signal from the subsurface reflection is being attenuated when it travels back to the surface.

25. The optical depth display for the Kansas Test Track (Figure 12) confirms the results from the power reflectance curve. There is one predominant interface reflection at the bottom of the ballast between layers 2 and 3 (see Table 1 for layer identification). There are three other small peaks on the optical depth display: one at zero optical depth (i.e. indicating a portion of the surface reflection), the second at an optical depth of 0.3 m (the interface between layer 1 and 2), and a third at an optical depth of 1.64 m. Initially, one might interpret the peak at 1.64 m as the interference reflection between layers 3 and 4; however, since it is exactly twice the optical depth of the large peak at 0.82 m, it is suspected to be a false peak.

Kansas Test Track-fouled ballast

26. The power reflectance curve for the Kansas Test Track-fouled ballast (Figure 11b) shows a distorted oscillating signal which decreases in amplitude as the frequency increases. It has a much longer period of oscillation than for the first Kansas Test Track example and thus suggests the presence of a strong reflecting interface close to the surface. The average power reflectance for the two Kansas Test Track examples is approximately the same, indicating that the surface reflectances (or the surface materials) are approximately the same.

27. The optical depth display for the Kansas Test Track-fouled ballast (Figure 13) shows that the strongest reflecting interface occurred at the middle of the ballast (i.e. where the ballast was fouled). A reflection is still present from the bottom of the slag ballast but is found at a somewhat deeper optical depth than before due to the increased moisture content of the fouled ballast. The change in appearance between the two Kansas optical depth display (Figures 12 and 13) would be a strong indicator of potential embankment problems.

Pueblo Test Track

28. The power reflectance curve for the Pueblo Test Track shows a relatively clean oscillating signal (Figure 11c) which decreases in amplitude as the frequency increases. The period of oscillation is identical with that of the first Kansas Test Track example (see Figure 11a) suggesting that most of the subsurface energy is reflecting from a single interface. Note that the oscillating signal attenuates with frequency at a slower rate than for the Kansas Test Track (Figure 11a).

29. The optical depth display for the Pueblo Test Track (Figure 14) confirms the results from the power reflectance curve. A large peak can be found for the interface at the bottom of the crushed stone ballast material (between layers 2 and 3). Note that as with the optical depth display for the Kansas Test Track (Figure 12), a false peak is shown at an optical depth of 1.64 m. It is easily identified because it occurs in the middle of a layer. Other peaks are shown for the surface and between layers 1 and 2. With the exception of the smaller peak at zero optical depth, the optical depth display for the Pueblo Test Track is very much the same as that for the Kansas Test Track. In the test track descriptions (paragraphs 13 and 14), the Kansas Test Track was described as representing poor performance under traffic and the Pueblo Test Track was described as representing good performance under traffic; and therefore, the power reflectance and optical depth display cannot be used alone as direct indicators of good or poor performance. At best, the radar measurements can give indications of structure which must, in turn, be related to performance through knowledge of original construction and/or maintenance records.

Rock Island Test Track

30. The power reflectance curve for the Rock Island Test Track (Figure 11d) shows two major oscillating signals which decrease in amplitude as the frequency increases. This suggests that two reflecting interfaces are present in the embankment.

31. The optical depth display for the Rock Island Test Track shows two peaks for the ballast material: one between layers 1 and 2, and

the second at the bottom of the ballast material between layers 2 and 3. No other peaks can be seen on the curves.

WES Test Track

32. The power reflectance curve for the WES Test Track (Figure 11e) shows several oscillating signals which decrease in amplitude as the frequency increases. This suggests the presence of several reflecting interfaces in the embankment.

33. The optical depth display for the WES Test Track (Figure 16) shows that there are two major reflecting interfaces: one at the bottom of the ballast between layers 2 and 3, and the second between layers 3 and 4. There are also several smaller peaks: one at zero optical depth (i.e. indicating a portion of the surface reflection), a second at 0.3 m (the interface between layers 1 and 2), a third at approximately 4.0 m (the interface between layers 4 and 5), and a fourth (a false peak) at an optical depth of 5.4 m.

Discussion of Results

34. For all embankment profiles studied, the bottom of the ballast could be consistently detected by strong peaks in the optical depth display. For 2 of the 5 profiles (i.e. Kansas Test Track-fouled ballast and Rock Island Test Track), a strong peak was also displayed for the interface between the clean ballast and ballast with fines; on the remaining 3 profiles, a small peak was present but was of the same magnitude as false peaks. However, since this interface depth is the same thickness as that of a railroad tie, it can always be easily identified in the display.

35. In only one of the profiles (i.e. the WES Test Track) could a strong interface reflectance be detected below the ballast. Its presence is due to the low attenuation for the material above the interface and the large electrical contrast at the interface. All other interface reflections were either too small or the reflected signal were too strongly attenuated by the time they reached the surface to be detected on the optical depth display. Signals from deep interface

relections will generally be difficult to detect when the enbankment materials above the reflecting interface have high water contents and water contents for materials in adjacent layers do not differ appreciably.

36. Compared with the original input data, the peaks in the pulsed radar results locate the interfaces very well for interfaces with large electrical contrasts near the surface. Small interface reflections could be confused with false peaks caused by distortions in interface reflections. Some of the false peaks may be removed by more sophisticated processing and should be one of the areas considered for improvement in the radar system developed in the future.

37. It was noted that the attenuation is strongly dependent on frequency and that less attenuation occurs at the low frequency end than at the high frequency end of the band used in this study. Although the selection of the frequency band for this study was based on experience gained through tests with swept-frequency radar on highway materials and ease of construction of ground radar, additional information may be provided by comparing attenuation rates and signal strengths from frequency bands above 2.0 GHz and below 0.5 GHz with that from the 0.5-GHz to 2.0-GHz band. These additional frequencies may help to eliminate false peaks and detect deeper interfaces.

38. Reflection measurements similar to those presented in this study for the five railroad embankments could be expected for artificial interfaces. For example, peaks in the optical depth curves should be detected for interfaces caused by high water tables or by voids or cavities in such embankments. In a similar fashion, during the construction phase of these railroad embankments, artificial layers or targets could be placed at regular intervals in embankments so that during later periods the movement of these artificial layers or targets could be interpreted as foundation movement. These artificial layers could be very simple materials (i.e. thin layers of such materials as metal foils or plastic films with high dielectric constants or high magnetic permeability). These layers could be buried at different

depths along a short length of railroad embankment and then, during later radar surveys, the placement could be determined very accurately and used for further interpretation of radar measurements.

PART V: CONCLUSIONS AND RECOMMENDATIONS

Conclusions

39. Based on the results of the study reported herein, the following conclusions are considered warranted and support the feasibility of using radar measurements to define railroad embankment subsurface layer thicknesses and properties:

- a. Swept-frequency radar measurements over the frequency range of 0.5 to 2.0 GHz can be used to estimate power reflectance from the surface material of railroad embankment structures and to determine the amplitude of the subsurface contribution. These measurements make possible estimates of the electrical properties of each of the materials.
- b. Layered materials produce interference patterns in the power reflectance curves over the frequency range of 0.5 to 2.0 GHz. Interference patterns can be used to calculate both the optical thickness of each layer and, with an adjustment made for wave velocity in the material, the physical thickness of each layer.
- c. Interface reflections from the bottom of ballast material in railroad embankments should be detected with radar measurements whenever (as in the case of the 5 embankments used in this study) there is a significant contrast in the electrical properties of the ballast materials and the material upon which the ballast is placed.
- d. Significant differences in power reflectance patterns should be detected when the moisture content of ballast materials increases due to change in material properties (fouled ballast) or to water pockets (perched water table).

e. Deeper layers may be detected within the embankment with radar measurements, provided the attenuation rate through the upper material is low and the electrical contrast at the interface is high. However under most conditions, interface reflections below the ballast material will probably be difficult to detect from radar measurements over the 0.5 to 2.0 GHz frequency range.

Recommendations

40. It is recommended that:

a. An experimental radar system be designed and constructed to make measurements of power reflectance of railroad embankments to determine any operational problem that might exist in gathering data to define railroad embankment subsurface layer thicknesses and properties.

b. Comprehensive tests be initiated to determine the basic electrical properties of railroad embankment materials at various microwave frequencies and to establish correlations between these properties and material quality.

c. A study be conducted to improve the process of information extraction from the power reflectance curves so that the effects of distortion in the complex propagation path can be minimized.

REFERENCES

1. Lundien, J. R., "Determining Presence, Thickness, and Electrical Properties of Stratified Media Using Swept-Frequency Radar," Technical Report M-72-4, Nov 1972, U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.

2. Lundien, J. R., "Noncontact Measurements of Foundations and Pavements with Swept-Frequency Radar," Highway Research Record, No. 378,, Washington, D. C., 1972, pp 40-47.

3. Harris, F. J., On the Use of Windows for Harmonic Analysis with the Discrete Fourier Transform, Proceedings of the IEEE, Vol. 66, No. 1, Jan 1978.

4. Lundien, J. R., "Terrain Analysis by Electromagnetic Means; Laboratory Measurements of the Electromagnetic Propagation Constants in the 1.0 to 1.5 GHz Microwave Spectral Region," Technical Report No. 3-693, Report 5, Feb 1971, U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.

5. Von Hippel, A. R., Dielectric Materials and Applications, MIT Press, Cambridge, Mass., 1954.

Table 1

Electrical Properties of Embankments

Layer No.	Thickness (m)	Relative dielectric constant ε_r	Dielectric loss tangent tan δ_d	Relative magnetic permeability μ_r	Magnetic loss tangent tan δ_m
			Kansas Test Track		
1	0.154	4	0.030	1.05	0.062
2	0.254	4	0.040	1.05	0.062
3	0.1524	27	0.280	1.0	0
4	0.1524	24	0.275	1.0	0
5	0.6098	23	0.270	1.0	0
6	0.9146	23	0.265	1.0	0
	Subgrade	10	0.050	1.0	0
			Kansas Test Track-Fouled Ballast		
1	0.1524	4	0.030	1.05	0.062
2	0.254	10	0.050	1.05	0.062
3	0.1524	27	0.280	1.0	0
4	0.1524	24	0.275	1.0	0
5	0.6098	23	0.270	1.0	0
6	0.9146	23	0.265	1.0	0
	Subgrade	10	0.050	1.0	0
			Pueblo Test Track		
1	0.1524	4	0.055	1.0	0
2	0.254	4	0.060	1.0	0
3	0.9140	8	0.110	1.0	0
4	0.9140	5	0.100	1.0	0
5	0.3048	6.5	0.120	1.0	0
	Subgrade	4	0.055	1.0	0
			Rock Island Test Track		
1	0.1524	4	0.055	1.0	0
2	0.8382	5	0.080	1.0	0
3	0.9140	31	0.150	1.0	0
4	0.2286	27	0.150	1.0	0
5	0.2286	53	0.400	1.0	0
6	0.762	43	0.350	1.0	0
	Subgrade	31	0.300	1.0	0

(Continued)

Table 1 (Concluded)

Layer No.	Thickness (m)	Relative dielectric constant ε_r	Dielectric loss tangent $\tan \delta_d$	Relative magnetic permeability μ_r	Magnetic loss tangent $\tan \delta_m$
		WES Test Track			
1	0.1524	4	0.055	1.0	0
2	0.4573	4	0.060	1.0	0
3	0.6098	6	0.010	1.0	0
4	0.3049	13	0.270	1.0	0
5	0.6098	15	0.275	1.0	0
6	0.3049	20	0.280	1.0	0
	Subgrade	21	0.285	1.0	0

In accordance with letter from DAEN-RDC, DAEN-ASI dated 22 July 1977, Subject: Facsimile Catalog Cards for Laboratory Technical Publications, a facsimile catalog card in Library of Congress MARC format is reproduced below.

Lundien, Jerry R
Feasibility study for railroad embankment evaluation with radar measurements / by Jerry R. Lundien. Vicksburg, Miss. : U. S. Waterways Experiment Station ; Springfield, Va. : available from *National Technical Information Service, 1978.*
40, [2] p. : ill. ; 27 cm. (Miscellaneous paper - U. S. Army Engineer Waterways Experiment Station ; S-78-10)
Prepared for U. S. Department of Transportation, Transportation Systems Center, Cambridge, Mass., under Reimbursable Agreement No. 76-41.
References: p. 40.

1. Computerized models. 2. Embankments. 3. Feasibility studies. 4. Measurement. 5. Radar. 6. Railroad engineering. 7. Railroads. 8. Slope protection. I. Transportation Systems Center. II. Series: United States. Waterways Experiment Station, Vicksburg, Miss. Miscellaneous paper ; S-78-10.
TA7.W34m no.S-78-10